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(54) Title: SYSTEM FOR HYDROGEN GENERATION

(57) Abstract: The present invention relates to a composition and method for storage and controlled release of hydrogen. In par-ticular, the present invention relates to the use of borohydride based solutions as a hydrogen storage source and a catalyst system to release hydrogen therefrom.

SYSTEM FOR HYDROGEN GENERATION

CROSS REFERENCE TO RELATED APPLICATION

This application claims priority of U.S. patent application ser. no. 09/479,362 filed January 7, 2000, which is incorporated herein by reference in its entirety.

FIELD OF THE INVENTION

The present invention relates to a system for generating hydrogen gas. In particular, the present invention relates to a hydrogen generation system including a stabilized metal hydride solution and a catalyst system.

BACKGROUND OF INVENTION

Hydrogen is a "clean fuel" because it can be reacted with oxygen in hydrogen-consuming devices, such as a fuel cell or combustion engine, to produce energy and water. Virtually no other reaction byproducts are produced in the exhaust. As a result, the use of hydrogen as a fuel effectively solves many environmental problems associated with the use of petroleum based fuels. Safe and efficient storage of hydrogen gas is, therefore, essential for many applications that can use hydrogen. In particular, minimizing volume and weight of the hydrogen storage systems are important factors in mobile applications.

Several methods of storing hydrogen currently exist but are either inadequate or impractical for wide-spread consumer applications. For example, hydrogen can be stored in liquid form at very low temperatures. Cryogenic storage, however, only provides a volume density of 70 grams of hydrogen per liter, which is clearly insufficient for consumer applications. In addition, the energy consumed in liquefying hydrogen gas is about 60% of the energy available from the resulting hydrogen. Finally, liquid hydrogen is not safe or practical for most consumer applications.

An alternative is to store hydrogen under high pressure in cylinders. However, a 100 pound steel cylinder can only store about one pound of hydrogen at about 2200 psi, which translates into 1% by weight of hydrogen storage. More expensive composite cylinders with special compressors can store hydrogen at higher

5   pressures of about 4,500 psi to achieve a more favorable storage ratio of about 4% by weight. Although even higher pressures are possible, safety factors and the high amount of energy consumed in achieving such high pressures have compelled a search for alternative hydrogen storage technologies that are both safe and efficient.

Other methods of hydrogen storage include the use of chemical

10   compounds that either (i) chemically react with water or other species to generate hydrogen or (ii) reversibly adsorb and then release the hydrogen. However, these methods and compounds suffer from many deficiencies, which make them unsuitable for use in consumer applications. These deficiencies include, high cost, poor safety, poor hydrogen storage capacities, decreased reversibility, poor hydrogen generation

15   capacities, poor control of hydrogen generation, and high system complexities.

In view of the above, there is a need for safer, more effective methods of storing and recovering hydrogen. In addition, there is a need to meet the above requirements while minimizing overall system volume and weight. It is, therefore, an object of the present invention to provide safer and more efficient methods for storing

20   and generating hydrogen. These and other objects of the invention will become more apparent from the detailed description and examples that follow.

SUMMARY OF THE INVENTION

The present invention provides a supported hydrogen generation catalyst having molecules of a hydrogen generation catalyst bound to, entrapped

25   within, and/or coated onto a substrate. Also provided is a process for making these catalysts, which includes: (A) contacting a substrate with a solution having a transition metal ion; and (B) contacting the resulting substrate of (A) with a reducing agent.

In another embodiment, the present invention also provides a process

30   for producing a supported hydrogen generation catalyst by electrochemical plating.

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This process includes: placing a conductive substrate in a solution having a transition metal ion; and applying a voltage to the substrate to thereby electrochemically plate a transition metal coating onto the substrate. Preferably, a varying voltage is applied to obtain a transition metal black coating.

5   In still another embodiment, the present invention provides a process for producing a supported hydrogen generation catalyst by chemical vapor deposition. This process includes: evaporating a transition metal complex comprising a transition metal ion and a chemical vapor deposition complexing compound; recondensing the transition metal complex onto a substrate; and applying a reducing agent to the

10   transition metal complex that is deposited on the substrate.

           In still another embodiment, the present invention provides a process for producing a supported hydrogen generation catalyst by coating a substrate with a transition metal via sputter deposition.

           The present invention also provides a hydrogen generation system,

15   which includes a stabilized metal hydride solution and a hydrogen generation catalyst system. The stabilized metal hydride solution has a metal hydride and water. The stabilized metal hydride solution can further include a stabilizing agent. The catalyst system includes a hydrogen generation catalyst. Preferably, the catalyst system further includes a containment system.

20   BRIEF DESCRIPTION OF THE DRAWINGS

           Further objects and advantages of the present invention will be more fully appreciated from a reading of the detailed description when considered with the accompanying drawings wherein:

           Figure 1 provides a graph of hydrogen generation rates versus

25   concentration of sodium borohydride utilizing a supported catalyst according to the present invention;

           Figure 2 provides a graph of the volume of hydrogen generated versus time for several different reaction temperatures utilizing a ruthenium supported catalyst according to the present invention;

Figures 3A and 3B provide illustrations of one embodiment of the present invention that has no moving parts;

Figure 4 provide an illustration of another embodiment of the present invention that has a mechanical pump;

5   Figures 5A and 5B provide illustrations of another embodiment for the reaction chamber of the present invention.

Figures 6A, 6B, and 6C provide a scanning electron micrograph and two X-ray scan micrographs of a hydrogen generation catalyst having ruthenium supported on an ion exchange resin, according to the present invention;

10   Figures 7A, 7B, and 7C provide a scanning electron micrograph and two X-ray scan micrographs of a hydrogen generation catalyst having ruthenium supported on the fibers of a standard nylon rope, according to the present invention;

Figure 8 provides a graph of hydrogen generation rate versus time for a ruthenium supported hydrogen generation catalyst according to the present invention;

15   Figure 9 provides a graph of the total amount of hydrogen produced versus time for a ruthenium supported hydrogen generation catalyst according to the present invention;

Figure 10 provides a graph of hydrogen generation versus time for four different supported catalysts according to the present invention: a ruthenium

20   supported catalyst; a rhodium supported catalyst; a platinum supported catalyst; and a cobalt supported catalyst; and

Figure 11 provides a graph of hydrogen generation rate versus time for multiple test using the same ruthenium supported catalyst according to the present invention.

25   DETAILED DESCRIPTION OF THE INVENTION

The present invention provides a novel hydrogen generation catalyst and hydrogen generation system utilizing the catalyst. The hydrogen generation system includes (i) a stabilized metal hydride solution and (ii) a catalyst system. The hydrogen generation systems of the present invention efficiently and safely provide

30   hydrogen gas while avoiding many of the problems associated with prior methods of

hydrogen generation. Furthermore, overall weight and volume are minimized in the hydrogen generation systems of the present invention.

I.   The Stabilized Metal Hydride Solution

The stabilized metal hydride solutions of the present invention include 5   (i) a metal hydride, (ii) at least one stabilizing agent, and (iii) a solvent. The term "solution," as used herein, includes a liquid in which all the components are dissolved and/or a slurry in which some of the components are dissolved and some of the components are undissolved solids. The term "about," as used herein, means plus or minus 10% of the stated value.

10   Complex metal hydrides have been found to be useful in the hydrogen generation systems of the present invention. These complex metal hydrides have the general chemical formula MBH_4. M is an alkali metal selected from Group 1 (formerly Group IA) of the periodic table, examples of which include lithium, sodium or potassium. M may, in some cases, also be ammonium or organic groups. B is an 15   element selected from group 13 (formerly Group IIIA) of the periodic table, examples of which include boron, aluminum, and gallium. H is hydrogen. Examples of metal hydrides to be used in accordance with the present invention include, but are not limited to, $NaBH_4$, $LiBH_4$, KBH_4, NH_4BH_4, $(CH_3)_4NH_4BH_4$, $NaAlH_4$, $LiAlH_4$, $KAlH_4$, $NaGaH_4$, $LiGaH_4$, $KGaH_4$, and mixtures thereof. Without wanting to be limited by 20   any one theory, it is believed that metal hydrides, especially borohydrides, are most stable in water, i.e., the metal hydrides do not readily decompose when in contact with water. The following borohydrides are preferred: sodium borohydride ($NaBH_4$), lithium borohydride ($LiBH_4$), potassium borohydride (KBH_4), ammonium borohydride (NH_4BH_4), tetramethyl ammonium borohydride ($(CH_3)_4NH_4BH_4$), 25   quaternary borohydrides, and mixtures thereof.

Hydrogen gas (H_2) and borate (BO_2^-) are generated by reacting borohydride with water, as illustrated by chemical reaction (1) below.

$$BH_4^- + 2H_2O = BO_2^- + 4H_2 \qquad (1)$$
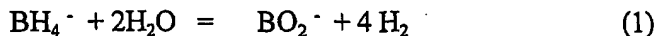
However, this chemical reaction occurs very slowly unless a catalyst is used. The 30   resulting borate is non-toxic and environmentally safe. In addition, borate can be

regenerated into borohydride. It is important to note that all of the hydrogen atoms present in borohydride and water are converted to hydrogen gas, and that half of the hydrogen atoms in the hydrogen gas produced by reaction (1) actually comes from the water. It is believed that the borohydride is capable of reducing protonic hydrogen

5   in water to produce hydrogen gas while the borohydride is simultaneously oxidized to borate and hydrogen gas.

A theoretical hydrogen conversion ratio can be calculated from reaction (1). For example, if lithium borohydride is used, the total weight of the reactants is 58 grams/mole: one mole of lithium borohydride weighs 22 grams, and

10   the two moles of water weighs 36 grams (2 x 18 grams/mole). Since 8 hydrogen atoms are produced, the theoretical hydrogen conversion ratio is 13.8% by weight of hydrogen (8 ÷ 58 x 100).

The maximum solubilities of various borohydrides are as follows: $NaBH_4$ - about 35% by weight of the stabilized metal hydride solution; $LiBH_4$ - about

15   7% by weight of the stabilized metal hydride solution; KBH_4 - about 19% by weight of the stabilized metal hydride solution. Weight percentages in excess of the maximum solubilities for each listed borohydride will result in a slurry, i.e., a liquid mixture having insoluble components. As is well known in the art, mixing or stirring means are typically used to help dissolve the solid components of a slurry with

20   additional water. For example, in the above calculation 22 grams of lithium borohydride in 36 grams of water provides a 37.9% by weight solution of lithium borohydride (22 ÷ 58 x 100). Since the 37.9% by weight solution of lithium borohydride exceeds its maximum solubility, this fuel mixture is a slurry.

Since two water molecules are consumed for each borohydride

25   molecule according to reaction (1), the concentration of all the remaining components (the cation, the borate, and the borohydride) will increase as the reaction continues. Therefore, twice as many water molecules as borohydride molecules are needed to sustain a constant rate of reaction. This excess water can be provided to the reaction in two ways: (i) charging the initial metal hydride solution with excess water, i.e.,

30   starting with a dilute solution, or (ii) adding more water from a separate source during or after the reaction. Note that a variety of water sources can be used, e.g., sea water.

The second alternative is preferred to minimize the initial starting weight of water plus borohydride. Adding water from a separate source during or after the reaction is viable because the main byproduct of hydrogen oxidation in a hydrogen-consuming device is water. A hydrogen-consuming device, as used herein, means a device that

5   uses hydrogen as a fuel, e.g., a fuel cell, combustion engine, a gas turbine. Thus, water generated from the hydrogen-consuming device can be added to the borohydride solution. Assuming that water is recycled from the fuel cell or engine, 8 weight units of hydrogen (4 from water and 4 from borohydride) can come from 22 weight units of lithium borohydride. The resulting theoretical hydrogen conversion

10 ratio is 36.36% by weight of hydrogen per unit of borohydride (8 ÷ 22 x 100). Therefore, the hydrogen generation system can include a slurry tank to store the borohydride and an adjacent mixing tank to add additional water obtained from the exhaust of the hydrogen consuming device, thereby allowing complete reaction of the borohydride while preventing the borohydride solution from drying out, i.e.,

15 preventing the components of the borohydride solution from precipitating out of solution.

The metal hydride solutions of the present invention include at least one stabilizing agent, since aqueous borohydride solutions slowly decompose unless stabilized. A stabilizing agent, as used herein, is any component which retards,

20 impedes, or prevents the reaction of metal hydride with water. Typically, effective stabilizing agents maintain metal hydride solutions at a room temperature (25 °C) pH of greater than about 7, preferably greater than about 11, and more preferably greater than about 13. As a result, the reaction of metal hydride with water can, therefore, be dependent on the concentration of the stabilizing agent, as illustrated by Figure 1,

25 which is a graph of hydrogen gas generation rate ([liters/sec-gram catalyst] x 10^5) vs. concentration of sodium borohydride (% by weight) at 25 °C and at various concentrations of sodium hydroxide, using IRA 400 exchange resin beads containing 5% ruthenium by weight and having a particle size of about 35 mesh.

Useful stabilizing agents include the corresponding hydroxide of the

30 cation part of the metal hydride salt. For example, if sodium borohydride is used as the metal hydride salt, the corresponding stabilizing agent would be sodium

hydroxide. Hydroxide concentrations in stabilized metal hydride solutions of the present invention are greater than about 0.1 molar, preferably greater than about 0.5 molar. Typically, metal hydride solutions are stabilized by dissolving a hydroxide in water prior to adding the borohydride salt. Examples of useful hydroxide salts

5   include, but are not limited to, sodium hydroxide, lithium hydroxide, potassium hydroxide, and mixtures thereof. Sodium hydroxide is preferred because of its high solubility in water of about 44% by weight. Although other hydroxides are suitable, the solubility differences between various metal hydrides and various hydroxide salts must be taken into account since such solubility difference can be substantial. For

10   example, adding too much lithium hydroxide to a concentrated solution of sodium borohydride would result in precipitation of lithium borohydride.

Other non-hydroxide stabilizing agents include those that can raise the overpotential of the metal hydride solution to produce hydrogen. These non-hydroxide stabilizing agents are preferably used in combination with hydroxide salts.

15   Nonlimiting examples of non-hydroxide stabilizing agents include compounds containing the softer metals on the right side of the periodic chart. Nonlimiting examples of these non-hydroxide stabilizing agents include compounds containing lead, tin, cadmium, zinc, gallium, mercury, and combinations thereof. Compounds containing gallium and zinc are preferred, because these compounds are stable and

20   soluble in the basic medium. For example, zinc and gallium form soluble zincates and gallates, respectively, which are not readily reduced by borohydride.

Compounds containing some of the non-metals on the right side of the periodic chart are also useful in stabilizing metal hydride solutions. Nonlimiting examples of these non-hydroxide stabilizing agents include compounds containing

25   sulfur, such as sodium sulfide, thiourea, carbon disulfide, and mixtures thereof.

II.   The Catalyst System

The hydrogen generation systems of the present invention also have a catalyst system, which includes a hydrogen generation catalyst. The hydrogen generation catalysts used herein activate the reaction of the metal hydride with water

30   to produce hydrogen gas. As are most catalysts, the hydrogen generation catalysts are

The catalysts used in the catalyst systems of the present invention preferably have high surface areas. High surface area, as used herein, means that the catalyst particles have small average particles sizes, i.e., have an average diameter of less than about 100 microns, preferably less than about 50 microns, and more

5   preferably less than about 25 microns. The chemical reaction of borohydride and water in the presence of the catalyst follows zero order kinetics, i.e., volume of hydrogen gas generated is linear with time. It is, therefore, believed that the reaction rate depends primarily on the surface area of the catalyst.

One method of obtaining catalyst particles with high surface areas is to

10   use catalysts with small average particle sizes. Although catalyst with small average particle sizes are preferred, small particles can be swept away by the liquid metal hydride solution if they are small enough to pass through the containment system. Such deficiencies can be avoided by forming large aggregates of the small catalyst particles. Large aggregate catalyst particles, as used herein, are masses or bodies

15   formed from any small catalyst particles by well-known powder metallurgical methods, such as sintering. These metallurgical methods can also be used in making various convenient shapes. It is believed that these large aggregate catalyst particles maintain high surface areas because they are very porous.

Alternatively, the hydrogen generation catalysts can be formed into

20   fine wires or a mesh of fine wires. These fine wires have a diameter of less than about 0.5 mm, preferably less than about 0.2 mm, and more preferably less than about 20 microns. In this embodiment, the fine wires of catalysts do no require a containment system, since the fine wires of catalyst will provide a sufficient surface area for reaction with the metal hydride solution without the drawback of being swept away by

25   the liquid metal hydride solution.

Preferably, the catalyst systems also include a containment system for the catalyst. The containment system employs any physical, chemical, electrical, and/or magnetic means to separate the hydrogen generation catalyst from the reacted metal hydride solution. As would be evident to one skilled in the art, the need for a

30   particular containment system will depend on the particular application of the system for hydrogen generation. For example, if an uncontrolled supply of hydrogen is

needed and no reuse of the system is desired, no containment system is needed. The stabilized metal hydride solution and the hydrogen generation catalyst can be separately packaged and combined when hydrogen is needed. Even this system can be reusable, if the hydrogen generation catalyst can be later separated to allow

5   regeneration of the reacted metal hydride solution. If a reusable and controllable system is desired, a containment system can be used to produce hydrogen when needed, as described below.

In its simplest form, the containment system is a liquid and gas permeable mesh that traps or holds particulate catalysts, while allowing liquids and

10   gases to pass freely through the containment system. In this embodiment the catalyst particles are larger than the spaces provided by the containment system. For example, metal hydride solution can flow into the containment system to react with the catalyst, while oxidized metal hydride, hydrogen gas, and unreacted metal hydride can easily pass out of the containment system. Alternatively, the containment system containing

15   the catalyst can be lowered into the metal hydride solution when hydrogen is needed.

In this embodiment, the containment system is a porous or mesh material, which is preferably stable in the metal hydride solution. Porous or mesh materials can be formed into any configuration known in the art, which would keep the catalyst particles in a confined area while allowing entry and egress of liquids and

20   gases. For example, a pouch or tea bag configuration can be used to encapsulate the catalyst particles, while allowing metal hydride solution and hydrogen gas to flow freely therethrough. Alternatively, the catalyst particles can be encapsulated in a removable tube or cylinder, wherein the ends of the cylinder are covered with the porous or mesh material. Porous or mesh material that are useful herein include

25   ceramics, plastics, polymers, nonwovens, wovens, textiles, fabrics, carbons, carbon-fibers, ion exchange resins, metals, alloys, wires, meshes, and combinations thereof. Typically, the porous or mesh material is in the form of a sheet. Nonlimiting examples of porous or mesh material include nylon screens and stainless steel screens.

In another embodiment, separately packaged metal hydride solution

30   and hydrogen generation catalyst can be combined when hydrogen is needed. Upon completion of the reaction, a containment system can then remove the catalyst by any

known separation technique, such as centrifugation, precipitation, filtration, electrophoresis, and electromagnetism. For example, metallic hydrogen generation catalysts can be separated by employing a containment system that has a magnetic element. Nonlimiting examples of metallic hydrogen generation catalysts include

5 iron, cobalt, nickel, and borides thereof. Alternatively, the mixture of catalyst and reacted metal hydride can be flushed out and later separated by a commercial processing center, which would recover the catalyst and regenerate the metal hydride solution.

In another embodiment, a contained high surface area catalyst can be

10 obtained by attaching or binding the hydrogen generation catalysts to a suitable substrate. The term "contained high surface area catalyst," as used herein, means that the catalyst is inherently maintained in a containment system and not free to migrate by itself, e.g., is attached to a substrate. In this embodiment, the metal hydride solution can pass over and/or through the substrate to react with the bound catalyst.

15 Thus, hydrogen production can be controlled by either contacting or separating the bound catalyst from the metal hydride solution. If the substrate is in particulate form, a further containment system, as described above, is preferred to encapsulate the supported catalyst. For example, high surface area transition metal particles can be dispersed onto a solution cast film. Many substrates (e.g., ion exchange resins and

20 plastics) can be dissolved into a solvent to form a solution or dispersion. The transition metal particles are then added. A solution cast film can be obtained by evaporating the solvent. The transition metal can be added in its salt or metal form and reduction steps can be taken if appropriate, as discussed below.

In a further example, a contained high surface area catalyst can be

25 obtained by binding or entrapping a transition metal catalyst onto and/or within a porous or nonporous substrate by chemical means. By porous is meant that the material is liquid and gas permeable. Generally, this process includes (i) dispersing a solution having a transition metal ion onto and/or within a substrate by contacting the solution with the substrate, and (ii) reducing the dispersed transition metal ions to the

30 neutral valence state of the transition metal, i.e., metallic form. Without wanting to be limited by any one theory, it is believed that this unique process binds and/or entraps

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wovens, KEVLAR fibers, polytetrafluoroethylene (PTFE), and combinations thereof. Since metal hydride solutions can have a high pH, substrates that do not dissolve or react with caustics are preferred. Also preferred are porous substrates with effective surface areas of greater than about 50 m^2/g or nonporous substrates with an average

5   diameter of less than about 50 microns.

When the substrate is in the form of beads, it is preferable to have the beads in a containment system, as described above, wherein the average diameter of the beads is greater than the spaces of the containment system. Furthermore, if the substrate has a surface treatment, such treatments can be removed by appropriate

10   methods, such as by boiling or applying a solvent. For example, substrates treated with wax can be boiled. Alternatively, the wax can be removed by using acetone. Similarly, the starch on textiles can be removed by boiling in water.

The substrates, except for the ion exchange resins described below, can be treated with any one of the hydrogen generation catalysts described above in the

15   following manner. The substrate can first soaked in a solution containing the hydrogen generation catalyst metal salt, e.g., a transition metal salt such as ruthenium trichloride. Solutions having concentrations close to saturation are preferred. This step disperses the catalyst metal salt into and/or onto the substrate. The treated substrate is then dried, typically with heat. Optionally, the treated substrate can be

20   filtered before being dried. Note that the treated substrate is not rinsed. It is believed that the drying step promotes absorption of the catalyst metal ions onto and/or within the substrate by removing the solvent. The dry, treated substrate is then subjected to a solution containing a reducing agent, such as sodium borohydride, at a concentration sufficient to provide complete reduction, e.g., 5% by weight of sodium borohydride.

25   Although this step can be conducted at room temperature, it is preferred to reduce the absorbed catalyst metal ions at an elevated temperature, e.g., greater than about 30 °C, to increase the reduction rate. It is believed that the reduction step converts transition metal ions into its neutral valence state, i.e., the metallic state. After rinsing with water, the substrate is ready for use as a catalyst in the reaction of the metal hydride

30   and water to produce hydrogen gas. The method can be repeated to obtain a desired loading of catalyst metal onto and/or within the substrate.

This method to obtain a contained high surface area catalyst can also be adapted to any technology known to those skilled in the art of surface coating technology. For example, this method can be adapted to utilize chemical vapor deposition technology (CVD) by forming a transition metal complex that can be

5   evaporated, i.e., boiled or sublimed, in a vacuum. The transition metal complex includes a transition metal ion, as described above, and a chemical vapor deposition complexing compound. Since the substrate is cold, the transition metal complex will recondense onto the substrate. Any suitable substrate, as described above, can be used. Any suitable chemical vapor deposition complexing compound that is known in

10   the art can also be used. A nonlimiting example of a useful chemical vapor deposition complexing compound is acetyl acetenate ("AcAc") or 2, 4 pentane dione. Nonlimiting examples of transition metal complexes useful in CVD include Ru(AcAc), Co(AcAc)$_3$, and isopropoxide. The transition metal complex that is deposited on the substrate can then be reduced by any of the above described reducing

15   agents.

Alternatively, this method can be adapted to utilize electroplating techniques, i.e., electroplating a conductive substrate in a solution having a transition metal ion. Useful transition metal ions are described above. The transition metal can be electroplated onto a conductive substrate, such as nickel or stainless steel fine wire,

20   screens comprising such fine wires, or metallic sheets. Typically, such fine wires can have an average diameter of less than about 20 microns, preferably less than about 10 microns, and more preferably less than about 2 microns.

In one preferred mode of electrochemical plating, a rough coating is obtained instead of the typical smooth or "bright coatings." Without wanting to be

25   limited by any one theory, it is believed that these rough coatings have a high surface area. These rough coatings are often black in color, and are typically referred to in the art of electrochemical plating by the element name followed by the word "black," e.g., platinum black or ruthenium black. Most of the transition metals described above can be coated as " transition metal blacks." The exact conditions may vary between the

30   elements, but the common parameter is application of a varying voltage during the plating process. "Varying voltage" means that the voltage is changed, alternated,

stepped up, or stepped down in a cyclic or noncyclic manner. For example, a DC voltage can be turned on or off over time. Alternatively, the current can be periodically reversed, or the voltage may be switched from a lower to higher voltage and then back to the lower voltage. It is also common to superimpose an AC signal

5   onto a DC source.

In still another example, this method to obtain a contained high surface area catalyst can also be adapted to utilize sputter deposition technology, e.g., physical vapor deposition, which is well known to those skilled in the art of surface coating technology. In sputter deposition, atoms of a metal surface are vaporized by

10   the physical ejection of particles from a surface induced by momentum transfer from an energetic bombarding species, such as an ion or a high-energy neutral atom, preferably an ion or atom from one of the inert noble gases. The target atoms evaporate into the vacuum chamber and then condense on the substrate to form a thin film. Typically, the substrate is mounted in a sputtering chamber, with one side

15   facing up or down toward a hydrogen generation catalyst target. After evacuating the chamber, an inert gas, such as argon, is used to backfill the chamber to a pressure from about 10 to about 50 millitorr (from about 1.3 to about 6.7 Pa). The sputtering process is initiated by applying a high voltage between the target and the chamber wall. The sputtering process is continued for an amount of time (typically a few

20   minutes but can range from less than about a minute up to about a few minutes) according to the desired thickness of the hydrogen generation catalyst. Upon completion of the sputtering, air is readmitted into the chamber to remove the coated substrate.

While most of these substrates simply absorb the solution of transition

25   metal salts, ion exchange resins offer some surprising and interesting characteristics. Ion exchange resins are porous polymeric materials having active groups at the end of the polymer chains. Typically, polymers used in ion exchange resins include, but are not limited to, polystyrene, epoxy amines, epoxy polyamines, phenolics, and acrylics. Ion exchange resins are classified into anionic exchange resins and cationic exchange

30   resins. These resins are commercially available as beads, typically having particle sizes from about 20 mesh to about 100 mesh. The resins are also available as sheets

and can be fabricated into any shape desired.

Anionic exchange resins attract anions because the active groups at the ends of the polymers have positive charges. Nonlimiting examples of positively charged active groups include a quaternary ammonium, tertiary amine, trimethyl

5   benzyl ammonium, and/or dimethyl ethanol benzyl ammonium. Commercial anionic exchange resins are typically supplied in the Cl⁻ or OH⁻ form, i.e., easily replaceable chloride ions or hydroxide ions are bound to the active groups having positive charges. Commercially available anionic exchange resins include, but are not limited to, A-26, A-36, IRA-400 and IRA-900, manufactured by Rohm & Haas, Inc., located

10   in Philadelphia, Pennsylvania; Dowex 1, Dowex 2, Dowex 21 K, Dowex 550A, Dowex MSA-1, and Dowex MSA-2, manufactured by Dow Corporation; Duolite A-101 D, Duolite A-102 D, and Duolite A-30 B; and Ionac A-540, Ionac A-550, and Ionac A-300.

Cationic exchange resins attract cations because the active groups at

15   the ends of the polymers have negative charges. Nonlimiting examples of negatively charged active groups include sulfonic acid, carboxylic acid, phosphonic acid, and/or aliphatic acid. Commercial cationic exchange resins are typically supplied in the Na⁺ or H⁺ form, i.e., easily replaceable sodium or hydrogen ions are bound to the active groups having negative charges. Commercially available cationic exchange resins

20   include, but are not limited to, Nafion resins, manufactured by Dupont Corp., located in Wilmington, Delaware; IRA-120 and Amberlyst 15 manufactured by Rohm & Haas, Inc., located in Philadelphia, Pennsylvania; Dowex 22, Dowex 50, Dowex 88, Dowex MPC-1, and Dowex HCR-W2 and Dowex CCR-1, manufactured by Dow Corporation; Duolite C-3, Duolite ES-63, and Duolite ES-80; and Ionac 240.

25   Anionic exchange resin beads are treated with the catalyst in the following manner. A transition metal salt is dissolved in an acid having the corresponding anion that can form an anionic complex of the transition metal. For example, ruthenium trichloride can be dissolved in hydrochloric acid to form chlororuthenic acid, wherein the ruthenium is contained in an anionic complex, i.e.,

30   $[RuCl_6]^{-3}$. Typically, the anionic complex of a transition metal is characterized by the chemical formula $[M^{y+}X_6]^{(y-6)}$, wherein M is a transition metal, y is the valence of the

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transition metal, and X is an anion with a single negative charge. The concentration
of the transition metal solution can be varied accordingly, but a concentration close to
saturation is preferred. The acidic solution containing the anionic transition metal
complex can then be exchanged onto the anionic exchange resin beads by contacting

5   the anionic exchange resin beads with the anionic transition metal solution.
Typically, this is done either by soaking the beads in the solution or dropwise adding
the solution onto the beads. Without wanting to be limited by any one theory, it is
believed that the anion associated with the active group of the resin is exchanged with
the anionic transition metal complex. Exchange, as used herein, means that the ion

10   associated with the active groups of the ion exchange resin, e.g., the chloride, is
substituted with the ion of the transition metal. As a result, a very strong chemical
(ionic) bond is formed between the anionic transition metal complex and the active
group of the ion exchange resin at each active group site.

        Upon exposure to a reducing agent, such as sodium borohydride, the

15   anionic transition metal complex is reduced at the exchange site to its neutral valence
state, i.e., the metallic state. The result is a distribution of transition metal catalyst
molecules in and/or on the resin. The process may be repeated to obtain higher metal
content if desired, because the reduction step restores the anion at the positively
charged active groups of the exchange resin. It is believed that the restored anion

20   associated with the active group is either the anion that had been formerly associated
with the transition metal, e.g., chloride from the $[RuCl_6]^{-3}$, or the reducing agent.
After rinsing with water, the treated anionic exchange resin beads are ready for use as
a catalyst in the reaction of the metal hydride and water to produce hydrogen gas.

        Catalyst treatment of cationic exchange resin beads require a slightly

25   different procedure, because the affinity of the cation transition metal complexes for
the cationic exchange resins is much weaker than the affinity of anion transition metal
complexes for the anionic exchange resins. Despite this additional complication,
cationic exchange resins are particularly useful because they can typically withstand
harsher environments, especially higher temperatures.

30   Although transition metals are formally written in their cationic
valence state, e.g. Ru^{+3}, transition metals form anionic complexes in the presence of

common complexing ions, such as chloride. Such anionic transition metal complexes would have little or no attraction for a cation exchange resin bead having negatively charged active groups. This can be avoided by using transition metal salts having non-complexing anions. Non-complexing anions, as used herein, refers to ions that

5   are typically very large and contain a central atom that is fully coordinated, thereby leaving little activity for further complexing with the transition metal. Nonlimiting examples of non-complexing anions of this type include perchlorate (ClO_4^-), hexaflourophosphate (PF_6^-), and tetrafluoroborate (BF_4^-), and mixtures thereof. Transition metal salts having non-complexing anions can be obtained via a

10   precipitation reaction with a transition metal salt and an equimolar amount of a compound having a non-complexing anion. The compound having the non-complexing anion is chosen so that the anion from the transition metal salt precipitates out with the cation associated with the non-complexing anion. For example, a solution of ruthenium trichloride can be reacted with an equimolar amount

15   of silver perchlorate solution. The chloride will precipitate out of solution as silver chloride and leave ruthenium perchlorate in solution. Since perchlorate ions can not complex like chloride ions, only the ruthenium will be hydrated in the cationic form, i.e., $[Ru \cdot xH_2O]^{3+}$, wherein x refers to the number of water molecules. It is believed that the hydrated ruthenium typically has a chemical formula $[Ru \cdot 6H_2O]^{+3}$.

20   The pH of the solution containing both transition metal ion and non-complexing ion should be adjusted to as close to 7 as possible without precipitation of ruthenium as a hydrated oxide, before contacting the cationic exchange resin beads. Preferably, the solution containing the transition metal ion and the non-complexing ion has a pH of greater than or equal to about 2, more preferably greater than or equal

25   to about 4, most preferably greater than or equal to about 7. This pH adjustment prevents hydrogen cations, H+, from competing for cationic sites, i.e., associate with the negatively charged active groups, of the cationic exchange resin. For example, if a 1 Molar solution of ruthenium is used and the pH is 2, ruthenium ions will outnumber hydrogen ions by a factor of 100. Although the ratio of ruthenium ions to

30   hydrogen ions at pH 2 is sufficient, the ratio would be even better at pH's closer to 7. Without wanting to be limited by any one theory, it is believed that upon contacting

the cationic exchange resin beads with the transition metal salt solutions, the positively charged transition metal ions exchange with the positive ions initially associated with the negatively charged active groups of the cationic exchange resin.

5   To insure high displacements of the transition metal ions without using excessive quantities of transition metal salt solutions, the exchange can be performed by contacting the cationic exchange beads with transition metal salt solutions in a tube or column. This method can also be used to treat the previously-described anionic exchange resins. The tube or column is usually mounted vertically and filled with cationic exchange beads. The solution containing transition metal ions and non-

10   complexing ions is allowed to pass through the column of beads. Typically, more dilute solutions are used first and then progressively more concentrated solutions can be used thereafter, thereby allowing the use of the concentrated solutions from the end of prior batches at the beginning of subsequent batches. Large quantities of catalyst treated cationic resin beads can be produced by utilizing a continuous counter-current

15   system that allows virtually complete utilization of ruthenium and complete saturation of the beads. A continuous counter-current system means contacting the more dilute ruthenium solution with the less treated beads and the more concentrated ruthenium solution with the more treated beads. After exchanging the transition metals onto and/or into the beads, the cationic exchange resins are rinsed with deionized water

20   and then reacted with a solution containing a reducing agent, such as sodium borohydride, to reduce the ruthenium to its neutral valence state. Higher transition metal content can be obtained by repeating the exchange and/or reduction steps, because the reduction step restores cations at the negatively charged active groups of the exchange resin. It is believed that the restored cation associated with the active

25   group is provided by the reducing agent, i.e., sodium from the sodium borohydride. After rinsing with water, the treated cationic exchange resin beads are ready for use as a catalyst in the reaction of the metal hydride and water to produce hydrogen gas.

III.   Controlled Hydrogen Generation

Since the metal hydride solutions of the present invention are

30   stabilized, hydrogen will not be generated in any appreciable rate unless the stabilized

- 20 -

solution contacts the catalyst. Upon removal of the catalyst, no hydrogen generation occurs. As a result, hydrogen generation can be easily controlled by either contacting with, or separating the catalyst from, the stabilized metal hydride solutions.

          The reaction of metal hydride with water is not only dependent on the

5   surface area of the catalyst and the concentration of stabilizing agent, as described above, but can also be dependent on temperature. Figure 2 plots hydrogen generated (liters) versus time (seconds) at various temperatures for a hydrogen generation system, wherein the catalyst system includes a 5% by weight of Ru on IRA 400 exchange resin and the metal hydride solution includes 20% by weight sodium

10   borohydride, 10% by weight sodium hydroxide, and the remainder water. As illustrated by Figure 2, higher rates of hydrogen gas production occur as the reaction temperatures increase. As discussed above, Figure 1 illustrates initial hydrogen generation rates for solutions of sodium borohydride with varying concentrations of sodium hydroxide stabilizer. Figure 1, therefore, shows that initial concentration of

15   stabilizers can also influence the initial rate of H_2 gas production. As can be recognized by one of ordinary skill in the art, any desired rate of reaction can be obtained by controlling one or more of any of the reaction parameters, e.g., the temperature of the reaction, choosing a particular catalyst and its configuration, and changing the concentration of the stabilizing agent.

20   The hydrogen generation systems described herein can be either a one-pass or a recirculating system. In a one-pass system, the metal hydride solution can be passed through or over the catalyst once and the waste solution is collected in a separate container or compartment. In a recirculating system, the waste solution is collected and passed over the catalyst multiple times before collecting the waste

25   solution in a separate reservoir. This design is preferably coupled with the water recycle method described above, wherein additional water is obtained from the water generated by a hydrogen-consuming device, such as a fuel cell.

          The waste reservoir can be either a separate container, or a bladder tank contained within the metal hydride solution reservoir. In this embodiment, the

30   bladder tank can be composed of a flexible, expandable material. Materials that are stable at pH's above about 8 are preferred. Useful bladder tank materials include, but

are not limited to, rubber, nylon, MYLAR, and TEFLON. Accordingly, the same

volume used to store the fresh metal hydride solution can also be used to contain the

reacted metal hydride solution. For example, unused volume is created in the storage

reservoir as the fresh metal hydride solution is consumed. The unused volume can

5   then be used for the expansion of the bladder tank, which can be filed with the reacted

metal hydride solution. The bladder tank, therefore, allows the fresh metal hydride

solution to be physically separation from the reacted metal hydride solution and

facilitates the recovery of the reacted metal hydride solution for disposal or

regeneration.

10   Several methods are available to contact the stabilized metal hydride

solution and the catalyst system. When hydrogen is required, the solution can be

pumped to a chamber containing the catalyst, or the catalyst can be moved into a tank

containing the solution. The metal hydride solution can be pumped either in batches

or continuously. The instantaneous demand for hydrogen can be met with a small

15   buffer tank that always holds some hydrogen gas. The hydrogen gas can be

immediately supplied upon demanded from this tank. The resultant pressure drop can

trigger the system to produce more hydrogen gas to keep a constant supply of

hydrogen available to the hydrogen consuming device.

             As illustrated by Figures 3A and 3B, one embodiment of the present

20   invention 10 has no moving parts and uses pressure equalization to move NaBH$_4$

solution from a reservoir 30 through a tube 50 connecting the bottom of the reservoir

into a reaction chamber 70 having a hydrogen generation catalyst system 80. The

reservoir is filled through a re-sealable air tight opening 20, and the pressure in the

reservoir 30 and reaction chamber 70 can be equalized through connecting tube 65

25   and control valve 60. When the NaBH$_4$ solution level in the reaction chamber reaches

the level of the hydrogen generation catalyst system 80, hydrogen is generated, as

illustrated by Figure 3A. The hydrogen generation catalyst system 80 includes a tube

made out of stainless steel screen, which contains the hydrogen generation catalyst.

While hydrogen is being generated, pressure differences will force NaBH$_4$ solution

30   away from the catalyst tube and stop hydrogen generation, as shown in Figure 3B.

When a sufficient amount of hydrogen has been consumed through control valve 90,

the pressure drop once again allows NaBH₄ solution to contact the catalyst, as shown
in Figure 3A. This compact, self-regulating design requires no external power source.

As illustrated by Figure 4, another embodiment of the present
invention 100 includes a reservoir 120 that is filled with NaBH₄ solution 140 via a re-
5   sealable airtight opening 110. The reservoir also has a head space 130, which acts as
a storage buffer for hydrogen gas, and a control valve 210 through which hydrogen
can be vented as needed. The bottom of the reservoir is connected via tube 160 to a
reaction chamber 180 having a hydrogen generation catalyst system 170, which
includes a tube made out of stainless steel screen containing the hydrogen generation
10   catalyst. The top of the reaction chamber 180 is connected to an upper portion of
reservoir 120 via tube 200. Hydrogen gas 190 is generated when a mechanical pump
150 in tube 160 meters NaBH₄ solution 140 through hydrogen generation catalyst
system 170. This design has very rapid response to hydrogen requirement. The pump
150 runs the borohydride solution over the catalyst and pressure builds up. Above a
15   certain pressure in head space 130, the pump 150 can reverse direction to drain the
catalyst chamber and thereby stop hydrogen production. The pump 150 then shuts
off. When the hydrogen pressure drops below a certain predetermined point in head
space 130, the pump 150 turns back on in the forward direction to refill reaction
chamber 180, generate additional hydrogen gas and replenish hydrogen pressures.

20   Figures 5A and 5B illustrate another embodiment of the catalyst
chamber 300. In this embodiment a flexible piece of stainless steel tubing 330 is used
as the catalyst chamber 300, which is attached via a pump (not shown) to a reservoir
(not shown) containing fresh metal hydride solution at one end 310 and a waste
reservoir (not shown) for the reacted metal hydride solution at the other end 320.
25   Both ends can be further covered by a suitable mesh, as described above. Figure 5A
is a top view of a coiled length of flexible stainless steel tubing, and Figure 5B is a
side view of the same tubing. Any appropriate length of tubing can be used, and the
tubing can be coiled, for example into 5 coils 340, to maximize use of space. The full
length of the tubing can be filled with a catalyst system, as described above.
30   Transition metal supported beads, resins, ribbons, and/or even rope can be used.
Alternatively, transition metal formed into wires, mesh, or particles (assuming that a

containment system, as described above, is used for the particles) can be used. A

pump, not shown, can be used to control hydrogen production by controlling flow of

metal hydride solution into the flexible tubing. The waste reservoir can also store

hydrogen, or the hydrogen can be vented off from the waste reservoir to a separate

5   hydrogen storage tank.

EXAMPLES

The following examples further describe and demonstrate

embodiments within the scope of the present invention. The examples are given

solely for the illustration purposes and are not to be construed as limitations of the

10   present invention, as many variations thereof are possible without departing from the

spirit and scope of the invention.

Example 1. Preparation of Catalysts Systems
with Anionic Exchange Resin Substrates

One gram of ruthenium trichloride was dissolved in 20 ml of 10%

15   hydrochloric acid to form chlororuthenic acid. The ruthenium is, therefore, contained

in an anionic complex of $[RuCl_6]^{-3}$. This solution containing the anionic transition

metal complex was exchanged by soaking onto Rohm & Haas IRA-400 anionic resin

beads having a mesh size of about 30. Other anionic resins, such as Rohm & Haas A-

26, can also be used in a similar manner. Since the resin beads are usually supplied in

20   the Cl⁻ form, the chloride ion was easily replaced. The exchange coefficient for this

type of complex was very high. It is, therefore, believed that almost all the available

exchange sites, i.e., positively charged active groups, were ionically bound with

$[RuCl_6]^{-3}$, as evidenced by a marked change in color from transparent yellow-orange

to dark red. The resin beads were then rinsed with water to remove excess acid and

25   ruthenium salts. This rinsing did not remove any bound ruthenium. Anionic resin

beads can absorb between 1.5 to 2 milli-equivalents of ruthenium per gram of resin

beads. Since the molecular weight of ruthenium is 101 g/mole, the resin beads were

weighed to determine the increase in weight. The exchanged resin beads were loaded

with about 5% by weight of ruthenium after about 3 to 4 treatments. Higher loadings

are possible if excess chloride is not present to compete for sites on the resin bead. This may be accomplished by using less hydrochloric acid initially or by raising the pH to about 2 to 3.

5   The exchanged resin beads were then treated with a reducing agent solution containing 20% by weight of sodium borohydride, 10% by weight of sodium hydroxide, and 70% by weight of water. The dark red resin beads turned black as the ruthenium complex was reduced to ruthenium metal. The resin beads were ready for use after rinsing with water. Typically, the resin beads treated with catalyst can be placed into a chamber made from a fine screen or other material that allows both

10   borohydride fuel and hydrogen gas to pass freely through the chamber while preventing the small beads from leaving.

           Figure 6A provides a micrograph from a scanning electron microscope (SEM) of a ruthenium treated resin bead at a magnification of 150X. The SEM used is model SR-50 manufactured by ISI Corporation. Figures 6B and 6C are X-ray scans

15   of the same ruthenium treated bead obtained from a UTW Micro Z detector manufactured by Evex Analytical Company. The detector is able to detect X-ray radiation at a particular frequency level for a particular element or compound. Figure 6B is an X-ray area scan showing the distribution of ruthenium (the lighter regions or the blue regions in the color micrograph) in the resin bead, and Figure 6C is an X-ray

20   area scan showing the distribution of carbon (the lighter regions or the yellow regions in the color micrograph) in the resin bead and also in the conductive carbon tape. A comparison of Figures 6B and 6C show that a significant amount of ruthenium was deposited on and throughout the resin bead. This result is expected, since the functional groups of the resin bead attracts the ruthenium ion. Figures 7A-7C provide

25   an SEM micrograph (Figure 7A) at a magnification of 540X and X-ray scans (Figures 7B and 7C) of the fibers of a standard nylon rope that was treated with ruthenium, as described above. A comparison of Figures 7B and 7C show that ruthenium did not permeate throughout the fiber, but rather only coated the surface of the fibers. The ruthenium is represented by the lighter regions in Figure 7B (the blue regions in the

30   color micrograph) and the darker regions in Figure 7C (the darker regions in the color micrograph). This shows that for the nylon fibers, straight diffusion coating resulted.

- 25 -

The resulting supported hydrogen generation catalysts were tested for hydrogen generation in a stabilized borohydride solution. One test compared hydrogen generation at various concentrations of sodium borohydride. The results are illustrated in Figure 1, which is a graph of hydrogen gas generation rate ([liters/sec-

5   gram catalyst] x 10^{-5}) vs. concentration of sodium borohydride (% by weight) at 25 °C at various concentrations of NaOH, using about 0.25 grams of Rohm & Haas IRA-400 exchange resin beads with 5% ruthenium by weight. A second test compared hydrogen generation at different reaction temperatures. The results are illustrated in Figure 2, which is a graph of hydrogen generation (liters) versus time (seconds) at

10   different temperatures for a hydrogen generation system, wherein the catalyst system includes about 0.25 grams of a 5% by weight Ru on Rohm & Haas IRA-400 exchange resin, and wherein the metal hydride solution includes 20% by weight sodium borohydride, 10% by weight sodium hydroxide, and 70% by weight water. A third test was conducted to determine the rate of hydrogen gas generation using 0.5 grams

15   of 5% by weight ruthenium on Rohm & Haas IRA-400 anionic exchange resin beads and a stabilized metal hydride solution having 20% by weight sodium borohydride, 5% by weight sodium hydroxide, and the remainder water. The results are provided in Figure 8, which is a graph of hydrogen generation rate (liters/min.) vs. time (seconds), and Figure 9, which is a graph of total hydrogen generated (liter) vs. time

20   seconds.

Example 1 was repeated to produce Rohm & Haas IRA-400 anionic exchange resin beads loaded with 5% by weight of ruthenium, platinum, and cobalt, respectively. The four different anionic exchange resin catalysts (i.e., ruthenium, rhodium, platinum, and cobalt) were tested for hydrogen generation. The results are

25   illustrated in Figure 10, which shows a plot of hydrogen volume (liters) vs. time (seconds) for the reaction of 0.25 grams of 5% by weight loading on Rohm & Haas IRA-400 anionic resin beads of each respective catalyst with a stabilized metal hydride solution containing 20% by weight of sodium borohydride, 10% by weight of sodium hydroxide, and 70% by weight water. As can be seen from Figure 10, the

30   anionic exchange resins with ruthenium provided the best hydrogen generations rates with the rest of the catalysts performing in the following order: rhodium > platinum >

cobalt.

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Example 2. Preparation of Catalysts Systems

with Ceramic and/or Carbon Substrates

</div>

Zirconium dioxide, ZrO_2, 8 mesh chips from Alfa-Aesar, located in

5   Massachusetts, were soaked in a solution of ruthenium trichloride at a concentration

of about 5% by weight. Without wanting to be limited by any one theory, it is

believed that the ruthenium trichloride was absorbed by the porous zirconium dioxide

bead. The beads were then filtered but not rinsed, and placed in a drying oven at 110

°C until dry. The ruthenium trichloride absorbed onto and/or within the beads were

10   then reduced with a solution including 20% by weight of sodium borohydride, 10%

by weight of sodium hydroxide, and 70% by weight of water. The beads were heated

in the solution for about 30 minutes at 65 °C. After rinsing with water, the beads were

ready for use in the hydrogen systems of the present invention.. Almost all other

porous substrates, such as ceramic and carbon substrates, can be converted in a similar

15   manner.

If other catalysts are desired, such as cobalt or nickel, the

corresponding chlorides of each catalyst can be used instead of the ruthenium

trichloride, as described above in Examples 1 and 2. A combination of catalysts is

also possible. This can be achieved in one of two ways. One method is to simply

20   premix the transition metal salts, e.g., cobalt chloride and ruthenium chloride. The

solution of the mixed transition metal salts is then used as described above in

Examples 1 and 2. The other method is to sequentially add and then reduce each

catalyst individually, as described above, onto the same substrate. Such sequential

addition and reduction provides layered absorption of the catalysts onto and/or into

25   the substrate.

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Example 3. Preparation of Catalyst Systems

with Cationic Exchange Resin Substrates

</div>

As described earlier with cationic resins, ruthenium trichloride was

reacted with silver perchlorate solution in a 1:3 molar ratio of Ru:Ag to obtain 0.5

<div align="center">- 27 -</div>

grams of elemental ruthenium. Precipitation of silver chloride was observed. After

filtering out the precipitate, sodium hydroxide was dropwise added to the remaining

solution of ruthenium perchlorate to adjust the pH to about 7. A vertical column was

packed with 10 grams of Rohm & Haas IRA-120 cation exchange resin beads. The

5   ruthenium perchlorate solution was repeatedly poured down the column until the

solution no longer had a reddish color, thereby obtaining cationic exchange beads

with 5% by weight of ruthenium (0.5 grams of ruthenium for 10 grams of resin

beads). After exchanging the ruthenium onto and/or into the beads, they were rinsed

with deionized water and reacted with a solution of sodium borohydride as the

10   reducing agent. The dark red resin beads turned black as the ruthenium complex was

reduced to ruthenium metal. After rinsing with water, the resin beads were ready for

use in the hydrogen systems of the present invention.

                        Example 4. Preparation of Catalyst Systems
                                by Electrochemical Plating

15   A nickel substrate was placed in a solution of 0.01 M ruthenium

trichloride, 0.01 HCl, and 0.1M KCl. Other conductive substrates, such as gold and

stainless steel can also be used. The substrate was then used as the cathode while the

voltage was varied from about 0.5 volts versus standard Calomel Electrode (SCE) to

about -1.5 volts SCE with a sweep rate of about 50 millivolts per second, thereby

20   providing a cycle time of about 40 seconds. The current was applied for about one

hour. The resulting coating on the substrate was black and dull in appearance. The

current can be supplied for as long as necessary to obtain the desired thickness. The

resulting ruthenium black coated substrates can be used in the hydrogen generation

systems of the present invention.

25   The hydrogen generation catalyst obtained from any one of the

methods/processes described herein are re-usable. For example, Figure 11 illustrates

hydrogen generation rates versus time for three test runs (i.e., the 7th run represented

by the circles, the 10th run represented by the line, and the14th run represented by the

squares) using the same ruthenium catalyst electroplated onto a nickel substrate

30   according to the process described in this example. A run in this particular

experiment is the passage of 2 L of 20% sodium borohydride solution over the same catalyst. Accordingly, the 7th run was conducted after 12 L of 20% sodium borohydride solution was passed over the catalyst; the 10th run was conducted after 18 L of 20% sodium borohydride solution was passed over the catalyst; and the 14th

5   run was conducted after 26 L of 20% sodium borohydride solution was passed over the catalyst. Figure 11 shows that even after repeated use, the catalysts of the present invention are re-usable and, furthermore, can produce about the same rate of hydrogen in subsequent runs.

We Claim:

1.   A process for producing a supported hydrogen generation catalyst,
comprising:
        (A)   contacting a substrate with a solution comprising a transition metal ion;
5   and

        (B)   contacting the resulting substrate of (A) with a reducing agent.

2.   The process according to claim 1, wherein
        the substrate comprises a material selected from the group consisting
of ceramics, plastics, polymers, copolymers, fluorinated polymers, fluorinated
10 copolymers, glass, fibers, ropes, nonwovens, wovens, textiles, fabrics, carbons,
carbon-fibers, ion exchange resins, metals, alloys, wires, wires, meshes, and
combinations thereof;
        the transition metal ion is an anion, a cation, an anion complex or a
cation complex of a transition metal selected from the group consisting of ruthenium,
15 iron, cobalt, nickel, copper, manganese, rhodium, rhenium, platinum, palladium,
chromium, silver, osmium, iridium, lanthanum, cerium, samarium, oxides thereof,
borides thereof, alloys thereof, and mixtures thereof; and
        the reducing agent is selected from the group consisting of metal
hydrides, hydrazine, hydrogen gas, glucose, hydroxylamine, carbon monoxide,
20 dithionate, sulfur dioxide, borohydride, alcohols, and mixtures thereof.

3.   The process according to claim 2, wherein the transition metal ion is an
anion, a cation, an anion complex or a cation complex of a transition metal selected
from the group consisting of ruthenium, rhodium, lanthanum, oxides thereof, borides
thereof, alloys thereof, and mixtures thereof.

25 4.   The process according to claim 1, wherein the substrate is an anionic
exchange resin, and the solution comprises an anionic complex of a transition metal.

5.   The process according to claim 4, wherein the solution is obtained by reacting a transition metal salt with an acid having the corresponding anion of said transition metal salt.

6.   The process according to claim 4, wherein the anionic complex of a

5   transition metal is characterized by the chemical formula $[M^{y+}X_6]^{(y-6)}$,

wherein, M is a transition metal, y is the valence of the transition metal, and X is an anion with a single negative charge.

7.   The process according to claim 1, wherein the substrate is a cationic exchange resin, and the solution comprises a transition metal cation and a non-

10   complexing anion.

8.   The process according to claim 7, wherein the solution has a pH of greater than or equal to about 0.

9.   The process according to claim 7, wherein the solution is obtained by the following process:

15   (A)   reacting a transition metal salt with a compound having a non-complexing anion to thereby promote precipitation of the anion, originally associated with the transition metal salt, and the cation, originally associated with the non-complexing anion; and

        (B)   separating out the precipitate.

20   10.   The process according to claim 9, wherein the non-complexing anion is selected from the group consisting of perchlorate (ClO_4^-), hexafluorophosphate (PF_6^-), tetrafluoroborate (BF_4^-), and mixtures thereof.

11.   The process according to claim 1, further comprising drying the resulting substrate of step (A) before contacting the substrate with the reducing agent,

25   wherein the the substrate comprises a material selected from the group consisting of

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ceramics, plastics, polymers, copolymers, fluorinated polymers, fluorinated copolymers, glass, fibers, ropes, nonwovens, wovens, textiles, fabrics, carbons, carbon-fibers, ion exchange resins, metals, alloys, wires, wires, meshes, and combinations thereof.

5   12.   A supported hydrogen generation catalyst obtained by the process according to claim 1.

13.   A supported hydrogen generation catalyst obtained by the process according to claim 4.

14.   A supported hydrogen generation catalyst obtained by the process
10   according to claim 7.

15.   A supported hydrogen generation catalyst obtained by the process according to claim 11.

16.   A process for producing a supported hydrogen generation catalyst, comprising:
15   (A)   placing a conductive substrate in a solution comprising a transition metal ion; and
        (B)   applying a voltage to the substrate to thereby electrochemically plate a transition metal coating onto the substrate.

17.   The process according to claim 16, wherein the voltage is a varying
20   voltage, and wherein the resulting transition metal coating is a transition metal black coating.

18.   The process according to claim 16, wherein the transition metal ion is an anion, a cation, an anion complex or a cation complex of a transition metal selected from the group consisting of ruthenium, iron, cobalt, nickel, copper, manganese,

rhodium, rhenium, platinum, palladium, chromium, silver, osmium, iridium,
lanthanum, cerium, samarium, oxides thereof, borides thereof, alloys thereof, and
mixtures thereof

19.   A supported hydrogen generation catalyst obtained by the process
according to claim 16.

20.   A process for producing a supported hydrogen generation catalyst,
comprising:

(A)   evaporating a transition metal complex comprising a transition metal
ion and a chemical vapor deposition complexing compound;

(B)   recondensing the transition metal complex onto a substrate; and

(C)   applying a reducing agent to the transition metal complex that is
deposited on the substrate.

21.   The process according to claim 20, wherein
the substrate comprises a material selected from the group consisting
of ceramics, plastics, polymers, copolymers, fluorinated polymers, fluorinated
copolymers, glass, fibers, ropes, nonwovens, wovens, textiles, fabrics, carbons,
carbon-fibers, ion exchange resins, metals, alloys, wires, wires, meshes, and
combinations thereof;
the transition metal ion is an anion, a cation, an anion complex or a
cation complex of a transition metal selected from the group consisting of ruthenium,
iron, cobalt, nickel, copper, manganese, rhodium, rhenium, platinum, palladium,
chromium, silver, osmium, iridium, lanthanum, cerium, samarium, oxides thereof,
borides thereof, alloys thereof, and mixtures thereof;
the reducing agent is selected from the group consisting of metal
hydrides, hydrazine, hydrogen gas, glucose, hydroxylamine, carbon monoxide,
dithionate, sulfur dioxide, borohydride, alcohols, and mixtures thereof; and
the chemical vapor deposition complexing compound is 2, 4 pentane
dione.

22.   The process according to claim 21, wherein the transition metal ion is an anion, a cation, an anion complex or a cation complex of a transition metal selected from the group consisting of ruthenium, rhodium, lanthanum, oxides thereof, borides thereof, alloys thereof, and mixtures thereof.

5   23.   A supported hydrogen generation catalyst obtained by the process according to claim 20.

24.   A process for producing a supported hydrogen generation catalyst, comprising coating a substrate with a transition metal via sputter deposition.

25.   The process according to claim 24, wherein

10   the substrate comprises a material selected from the group consisting of ceramics, plastics, polymers, copolymers, fluorinated polymers, fluorinated copolymers, glass, fibers, ropes, nonwovens, wovens, textiles, fabrics, carbons, carbon-fibers, ion exchange resins, metals, alloys, wires, wires, meshes, and combinations thereof; and

15   the transition metal ion is selected from the group consisting of ruthenium, iron, cobalt, nickel, copper, manganese, rhodium, rhenium, platinum, palladium, chromium, silver, osmium, iridium, lanthanum, cerium, samarium, oxides thereof, borides thereof, alloys thereof, and mixtures thereof.

26.   The process according to claim 25, wherein the transition metal ion is 20   an anion, a cation, an anion complex or a cation complex of a transition metal selected from the group consisting of ruthenium, rhodium, lanthanum, oxides thereof, borides thereof, alloys thereof, and mixtures thereof.

27.   A supported hydrogen generation catalyst obtained by the process according to claim 24.

28.   A supported hydrogen generation catalyst, comprising (i) a substrate; and (ii) molecules of a hydrogen generation catalyst bound to, entrapped within, and/or coated onto said substrate.

29.   The supported catalyst according to claim 28, wherein

5   the substrate comprises a material selected from the group consisting of ceramics, plastics, polymers, copolymers, fluorinated polymers, fluorinated copolymers, glass, fibers, ropes, nonwovens, wovens, textiles, fabrics, carbons, carbon-fibers, ion exchange resins, metals, alloys, wires, wires, meshes, and combinations thereof; and

10   the transition metal ion is selected from the group consisting of ruthenium, iron, cobalt, nickel, copper, manganese, rhodium, rhenium, platinum, palladium, chromium, silver, osmium, iridium, lanthanum, cerium, samarium, oxides thereof, borides thereof, alloys thereof, and mixtures thereof.

30.   The supported catalyst according to claim 28,

15   wherein the substrate is selected from the group consisting of ceramics, zeolites, perovskites, phosphates, fibers, fibrous materials, meshes, cationic exchange resins, and anionic exchange resins; and

               wherein the transition metal ion is an anion, a cation, an anion complex or a cation complex of a transition metal selected from the group consisting of

20   ruthenium, rhodium, lanthanum, oxides thereof, borides thereof, alloys thereof, and mixtures thereof.

31.   A hydrogen generation system, comprising:

(A)   a metal hydride solution, comprising a metal hydride and water; and

(B)   a hydrogen generation catalyst system, comprising a hydrogen

25   generation catalyst.

32.   The hydrogen generation system according to claim 31, wherein the metal hydride is selected from the group consisting of sodium borohydride, lithium borohydride, potassium borohydride, ammonium borohydride, tetramethyl ammonium borohydride, and mixtures thereof.

5   33.   The hydrogen generation system according to claim 31, wherein the metal hydride solution further comprises a stabilizing agent to provide a pH of greater than or equal to about 7.

34.   The hydrogen generation system according to claim 33, wherein the stabilizing agent is selected from the group consisting of hydroxide-containing

10   compounds selected from the group consisting of sodium hydroxide, lithium hydroxide, and potassium hydroxide; compounds containing a soft metal selected from the group consisting of lead, tin, cadmium, zinc, gallium, and mercury; and compounds containing a non-metal selected from the group consisting of sulfur; and mixtures thereof.

15   35.   The hydrogen generation system according to claim 34, wherein the stabilizing agent is selected from the group consisting of sodium hydroxide, lithium hydroxide, potassium hydroxide, sodium sulfide, thiourea, carbon disulfide, sodium zincate, sodium gallate, and mixtures thereof.

36.   The hydrogen generation system according to claim 33, wherein the

20   hydrogen generation catalyst, comprises (i) a substrate; and (ii) molecules of a transition metal bound onto, entrapped within, and/or coated onto the substrate.

37.   The hydrogen generation system according to claim 36, wherein the substrate comprises a material selected from the group consisting of ceramics, plastics, polymers, copolymers, fluorinated polymers, fluorinated

25   copolymers, glass, fibers, ropes, nonwovens, wovens, textiles, fabrics, carbons, carbon-fibers, ion exchange resins, metals, alloys, wires, wires, meshes, and

combinations thereof; and

the transition metal ion is selected from the group consisting of ruthenium, iron, cobalt, nickel, copper, manganese, rhodium, rhenium, platinum, palladium, chromium, silver, osmium, iridium, lanthanum, cerium, samarium, oxides

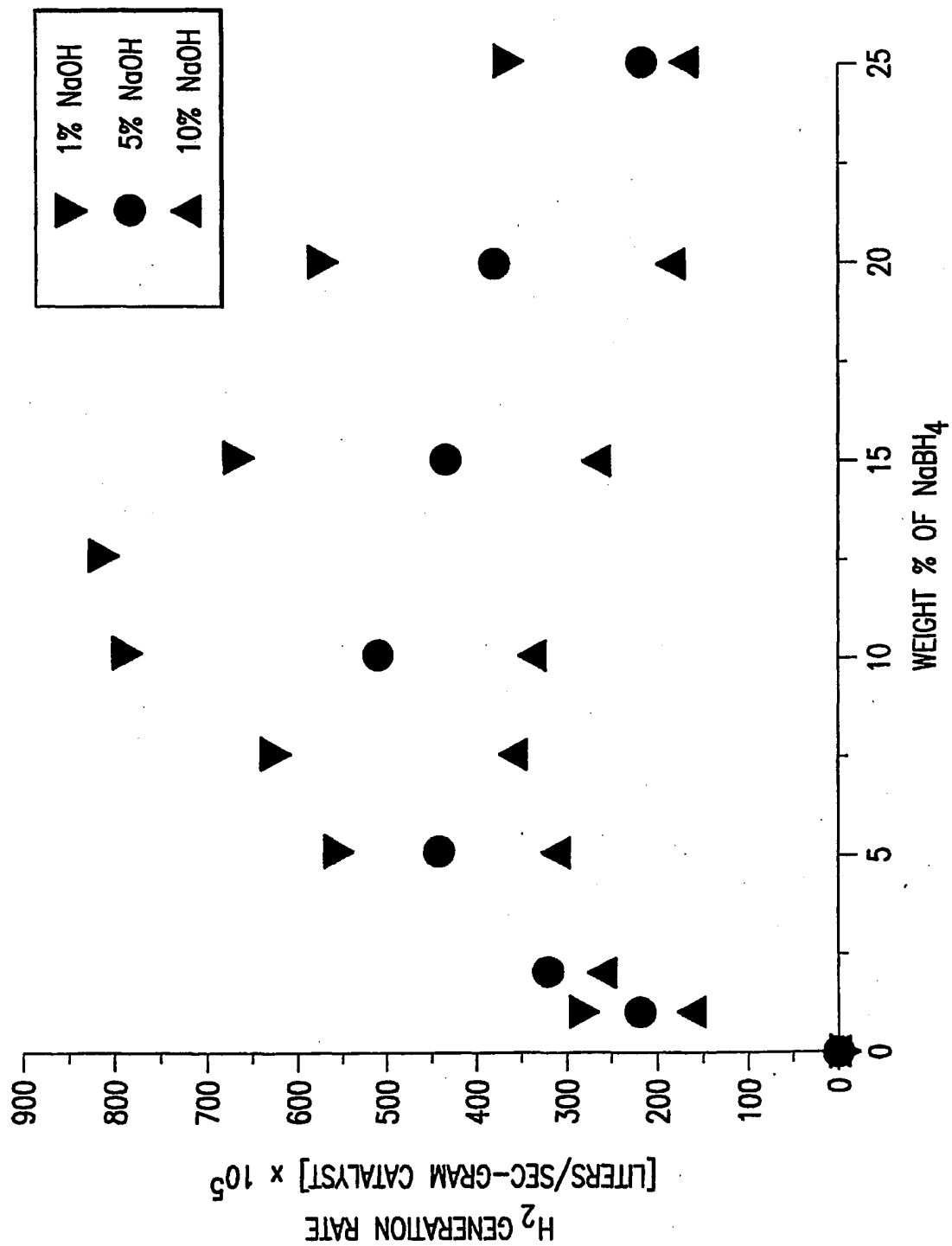5   thereof, borides thereof, alloys thereof, and mixtures thereof.

38.   The hydrogen generation system according to claim 37,

wherein the substrate is selected from the group consisting of ceramics, zeolites, perovskites, phosphates, fibers, fibrous materials, meshes, cationic exchange resins, and anionic exchange resins; and

10   wherein the transition metal ion is an anion, a cation, an anion complex or a cation complex of a transition metal selected from the group consisting of ruthenium, rhodium, lanthanum, oxides thereof, borides thereof, alloys thereof, and mixtures thereof.

39.   The hydrogen generation system according to claim 31, wherein the

15   hydrogen generation catalyst system, comprises a flexible tubing and a hydrogen generation catalyst in the flexible tubing.

40.   The hydrogen generation system according to claim 31, wherein the stabilized metal hydride solution further comprises water obtained from the reaction product of a hydrogen-consuming device.

20   41.   The hydrogen generation system according to claim 40, wherein the hydrogen-consuming device is selected from the group consisting of a fuel cell, a combustion engine, a gas turbine, and combinations thereof.
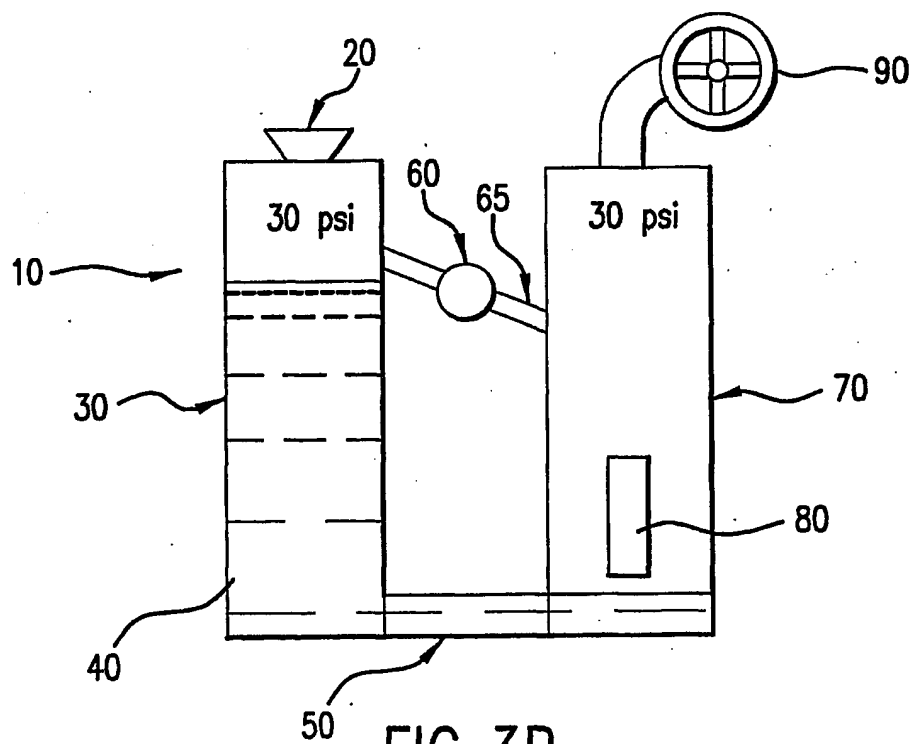
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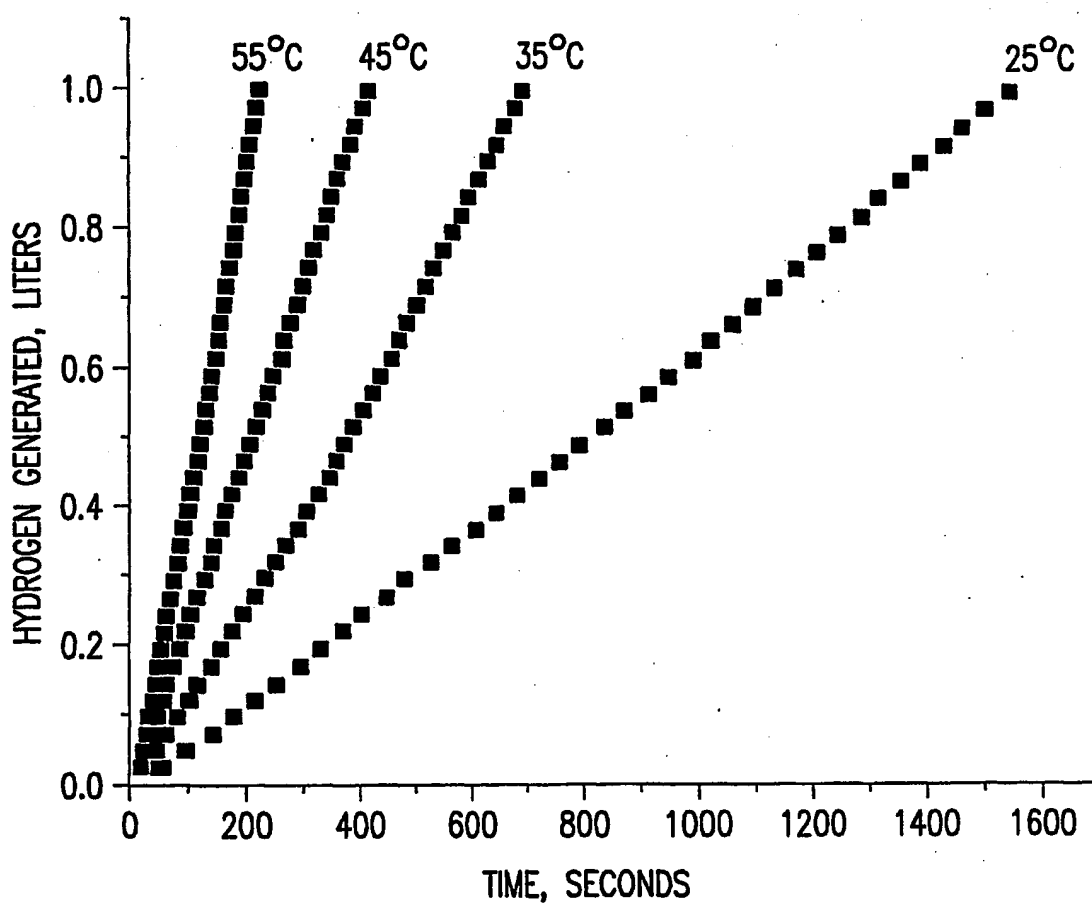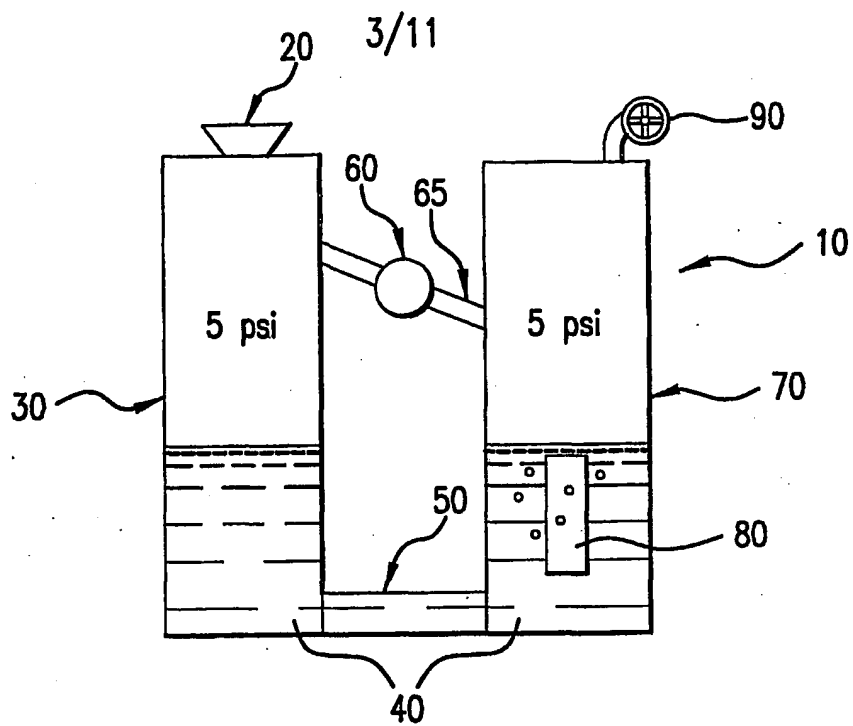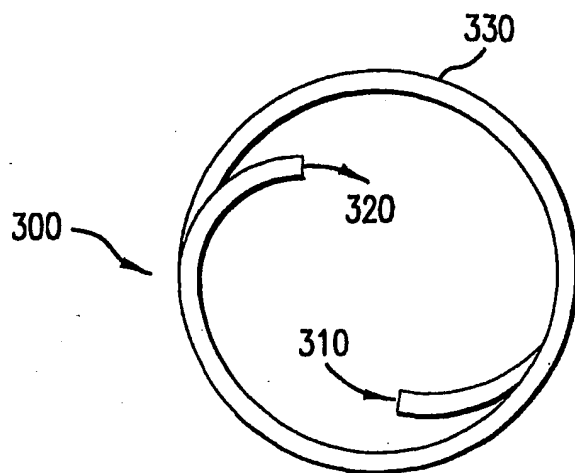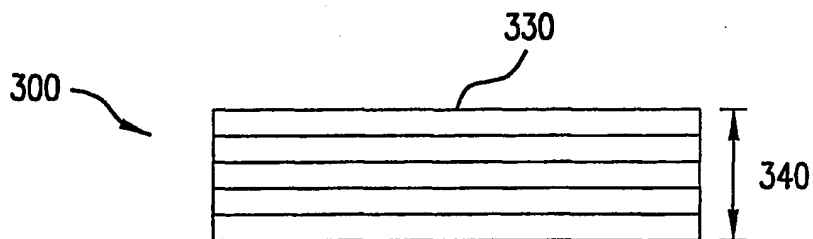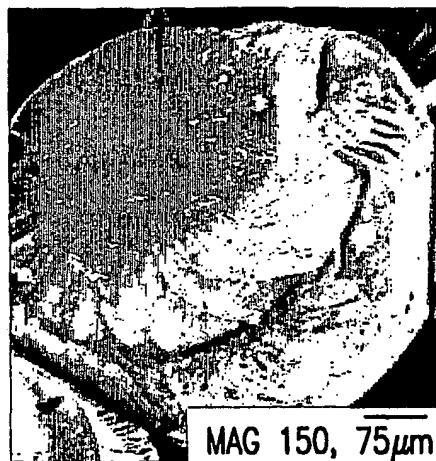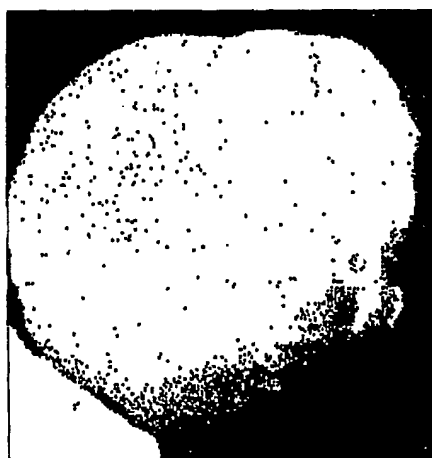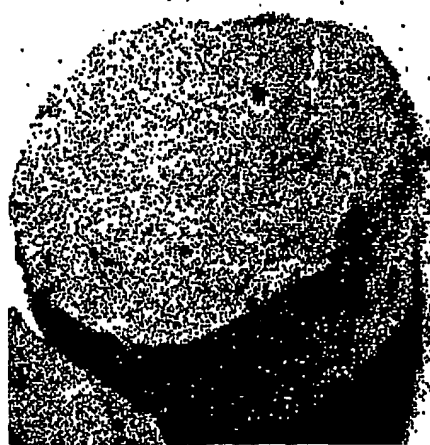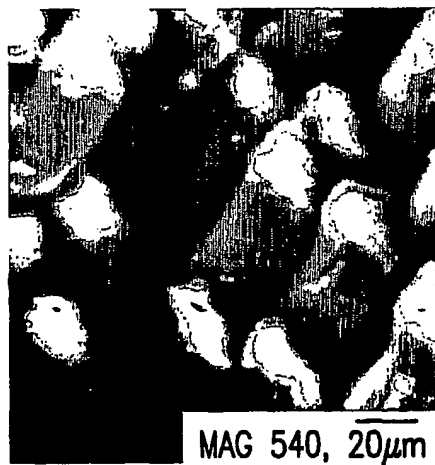
FIG.1

FIG.2

FIG. 3A

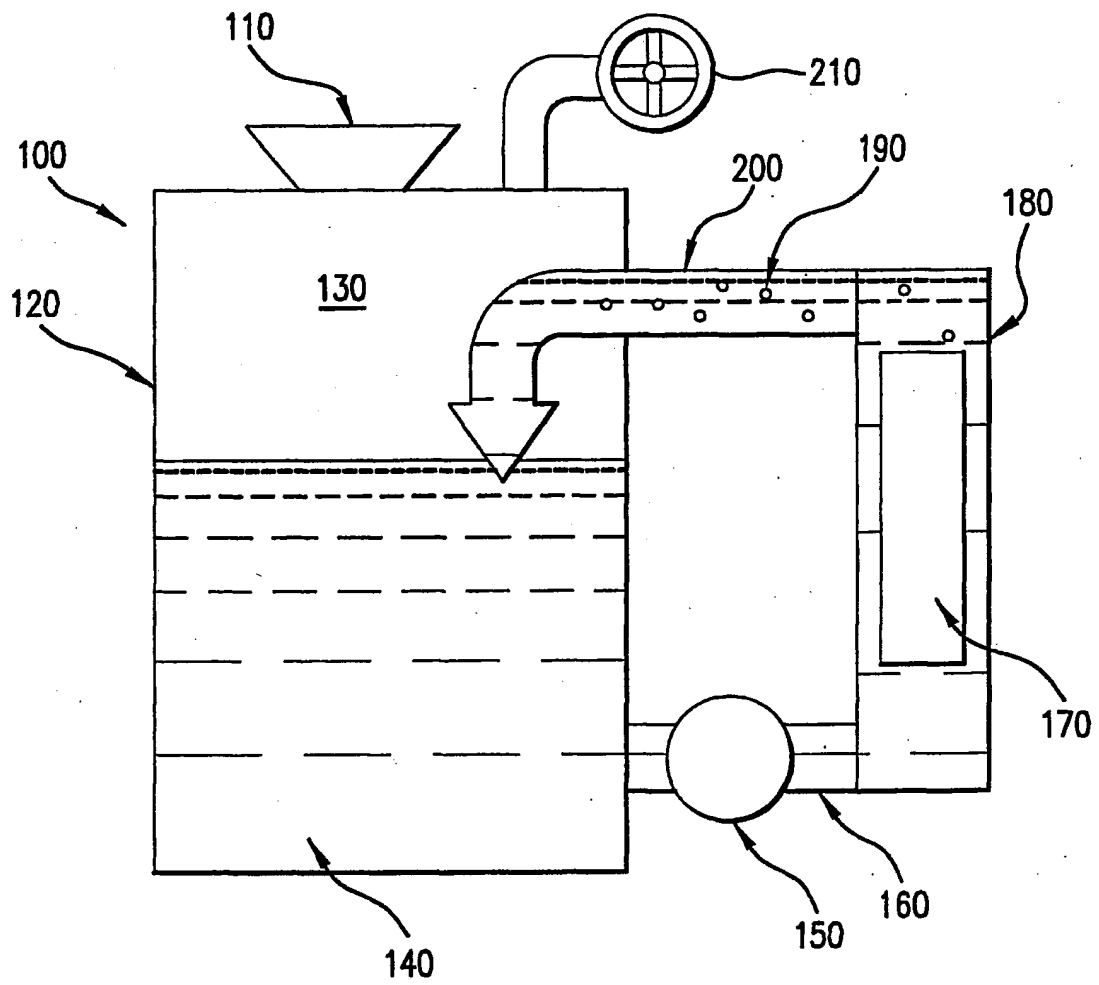FIG. 3B

FIG.4

FIG. 5A

FIG. 5B

MAG 150, 75μm

FIG.6A

FIG.6B

FIG.6C

MAG 540, 20μm

FIG.7A

FIG.7B
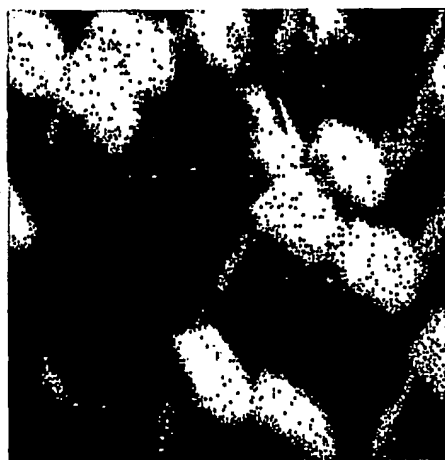
FIG.7C
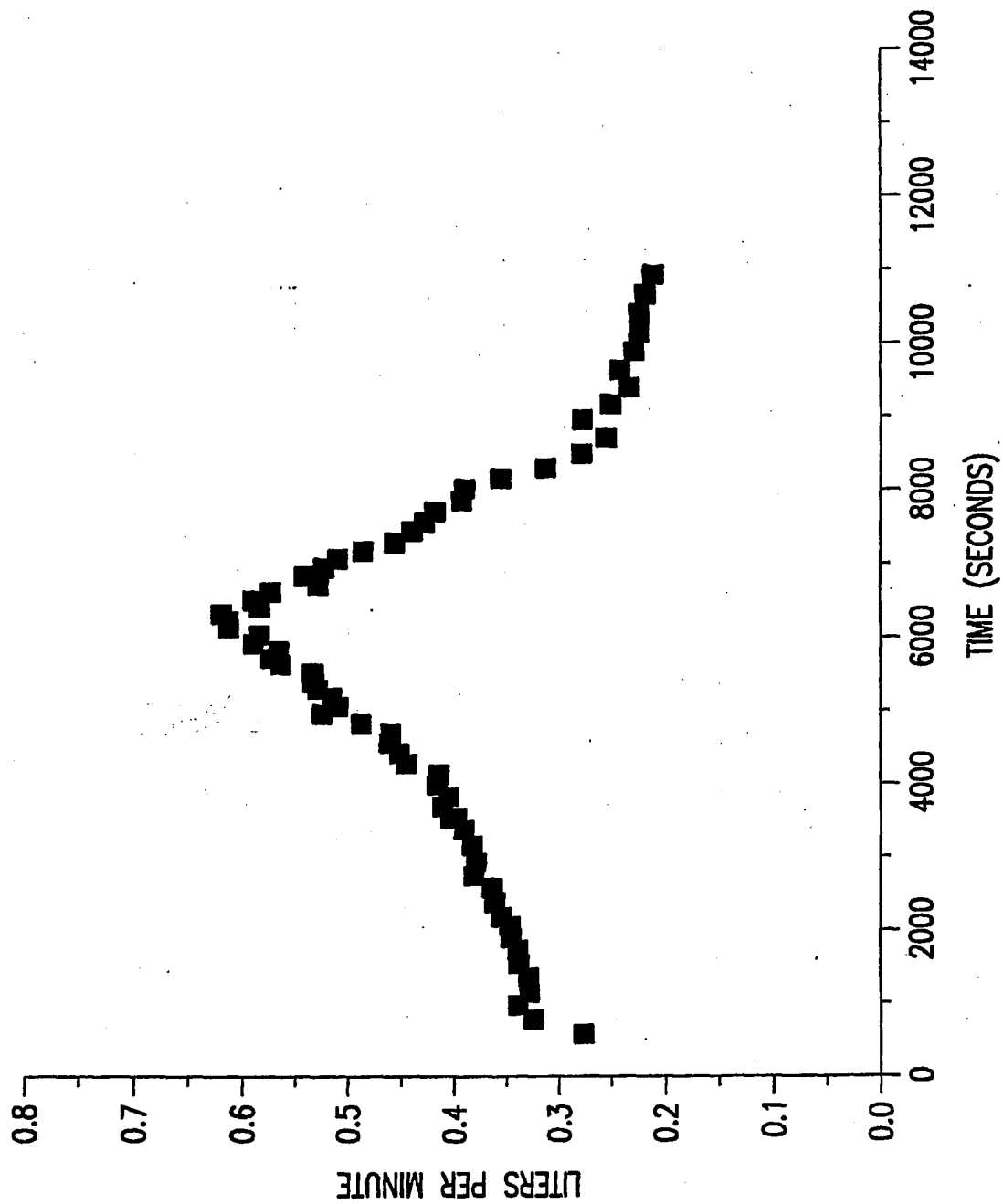
FIG.8

FIG.9
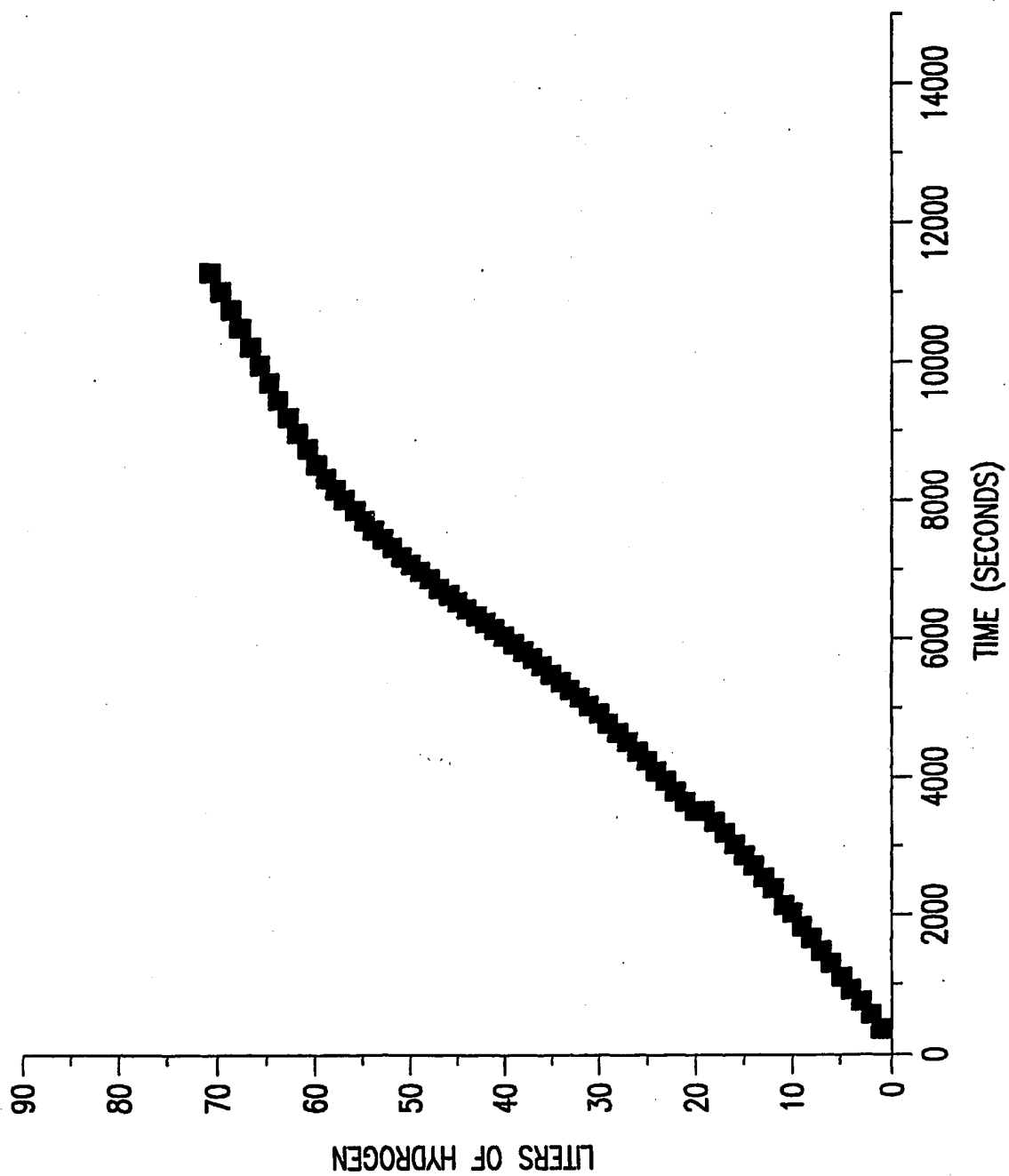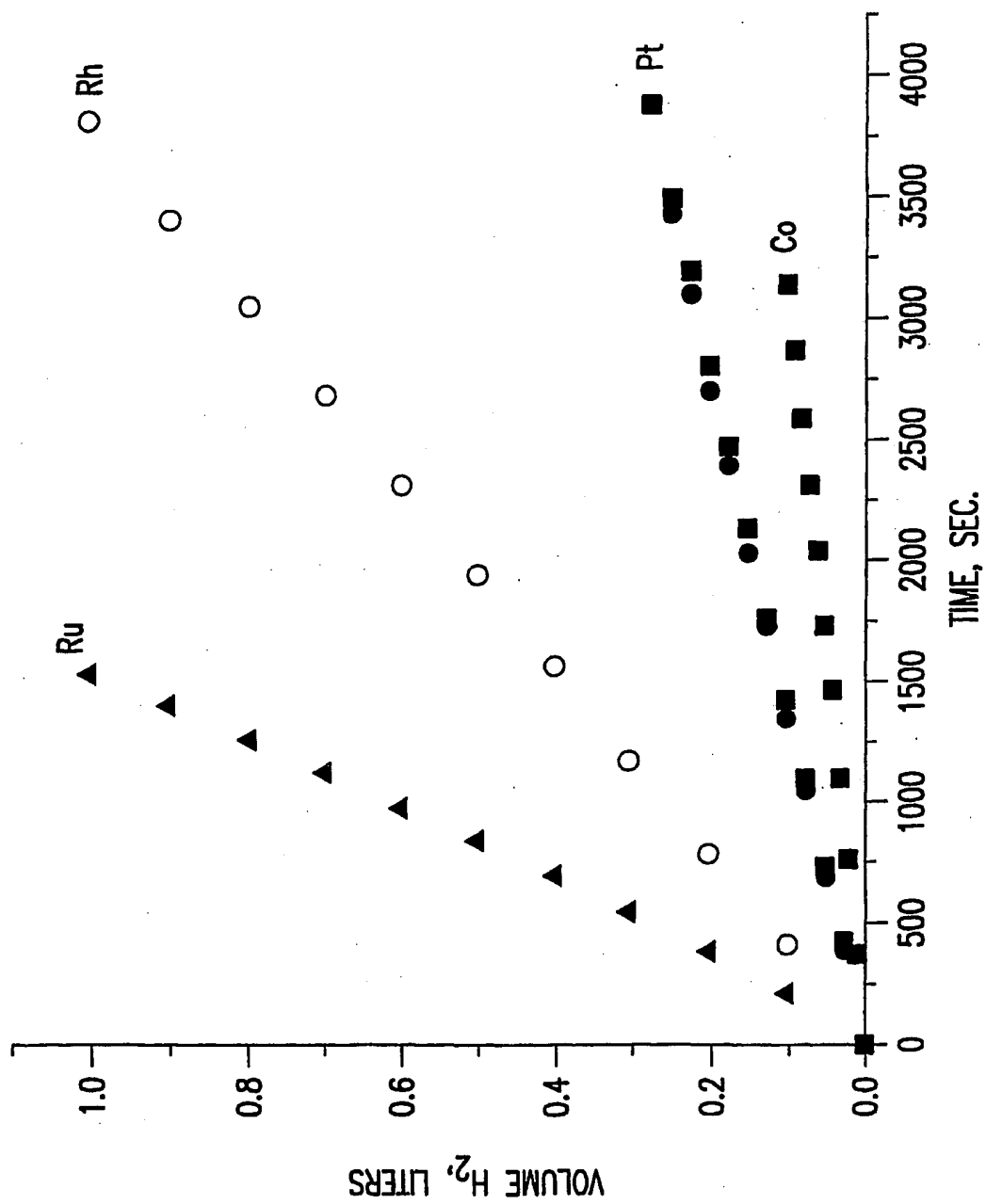
FIG.10
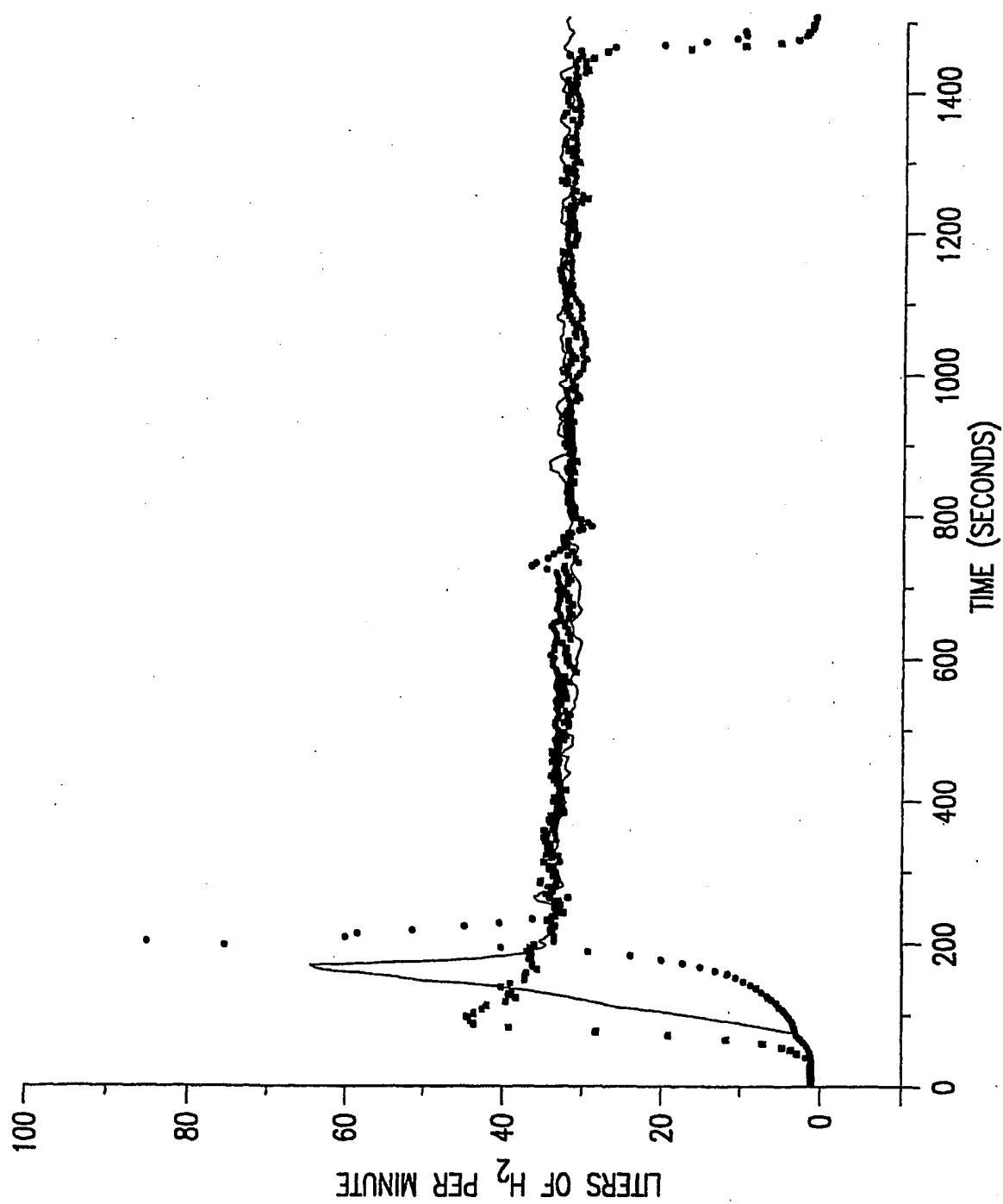
FIG. 11

	nal Application No
	PCT/US 01/00318

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7   C01B3/06

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7   C01B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 804 329 A (AMENDOLA STEVEN) 8 September 1998 (1998-09-08) column 4, line 22 - line 30	31
A	US 5 205 841 A (VAIMAN LEV A) 27 April 1993 (1993-04-27) column 3, line 34 - line 42	16
A	US 5 514 353 A (ADLHART OTTO) 7 May 1996 (1996-05-07) example 1	31
A	WO 98 30493 A (BRITISH NUCLEAR FUELS PLC ;FOSTER SIMON (GB); WAKEFIELD LEIGH (GB)) 16 July 1998 (1998-07-16) page 2, line 17 -page 4, line 24	31

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X	Further documents are listed in the continuation of box C.		X	Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
26 March 2001	02/04/2001

Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Authorized officer Clement, J-P

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A	US 5 372 849 A (MCCORMICK FRED B ET AL) 13 December 1994 (1994-12-13) column 1, line 23 -column 2, line 6; claim 1	20
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